光　子　学　报
ACTA PHOTONICA SINICA

引用格式：LV Mingxin，ZHANG Yipeng，HE Jianlang，et al. Research Progress of Vortex Beam Laser（Invited）[J]. Acta Photonica Sinica，2022，51（1）：0151105
吕铭鑫，张翼鹏，何健朗，等. 涡旋光激光器研究进展（特邀）[J]. 光子学报，2022，51（1）：0151105

涡旋光激光器研究进展（特邀）

吕铭鑫 1,2，张翼鹏 1,3，何健朗 1,2，胡小鹏 1,2，张勇 1,2
（1 固体微结构物理国家重点实验室（南京大学），南京 210093）
（2 南京大学 现代工程与应用科学学院，南京 210093）
（3 南京大学 物理学院，南京 210093）

摘　要：涡旋光激光器能够输出具有特定空间结构的高能量、高质量的涡旋光束。涡旋光束在光通讯、光操控、超分辨成像等领域都有潜在的应用前景。本文介绍了涡旋光束的产生原理及其应用，综述了近期涡旋光激光器的发展历程，同时也对涡旋光激光器的发展趋势进行了展望。

关键词：涡旋光；轨道角动量；激光器；光学参量振荡；光纤激光器
中图分类号：O437　　**文献标识码**：A　　**doi**：10.3788/gzxb20225101.0151105

0 Introduction

The laser，as a light source with excellent monochromaticity，coherence，directionality and energy density，has been widely used in industry，agriculture，communications and aerospace since its invention. The history of its development can be traced back to the concepts of stimulated absorption and stimulated radiation[1]. Recently，there has been increasing demand for a vortex beam that has a spiral wavefront，i.e.，a helical phase with a period of $2\pi l$. Here，l is the topological charge. In 1992，ALLEN L et al revealed the relationship between the spiral wavefront and Orbital Angular Momentum（OAM）[2]，i.e.，each photon of vortex beam carries an OAM of $l\hbar$（where $\hbar$ is the reduced Planck constant）. In addition to the amplitude，phase，polarization and propagation properties，the OAM is also considered as an essential parameter for a vortex beam. These unique properties boost the applications of vortex beam in micromachining，optical communications，optical manipulation，superresolution imaging，precision measurement，nonlinear and quantum optical applications[3-14]. The vortex beam laser becomes a key device that outputs a high-quality vortex beam. Currently，the researches on vortex beam laser have been focused on realizing high efficiency，high mode purity，and system integration.

In this paper，we will introduce the recent developments of vortex beam laser. First，we compare the vortex beams generated by using active and passive methods. Then，the research progresses on vortex beam laser，including solid-state laser，optical parametric oscillator，fiber laser and on-chip integrated laser，are reviewed. Finally，we discuss the prospects of the future vortex beam laser.

1 Vortex beams

One typical vortex beam is Laguerre-Gaussian（LG）beam，which is the eigen solution of the scalar Helmholtz equation，$\nabla^2 u + k^2 u = 0$，in cylindrical coordinates. It can be expressed as

---

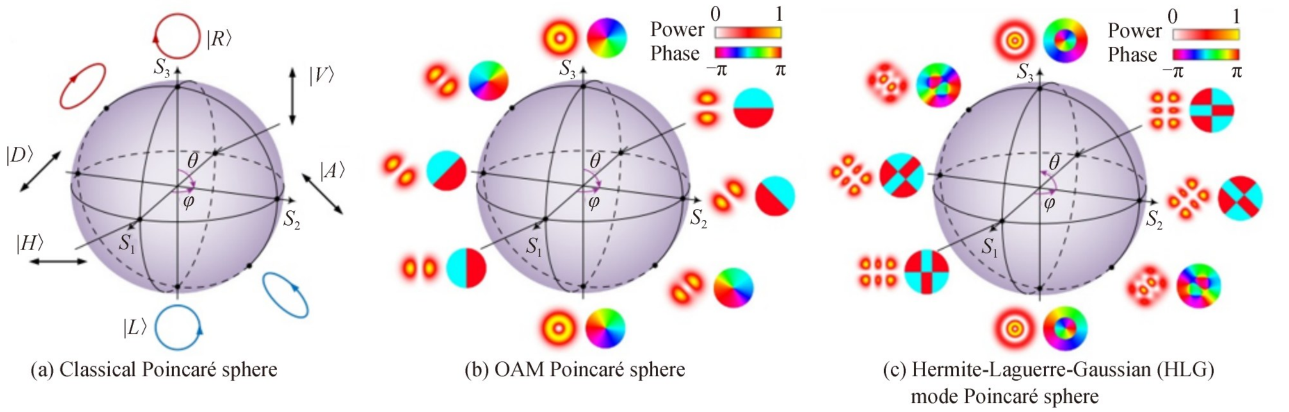
Foundation item：National Natural Science Foundation of China（Nos.91950206，11874213），National Key Research and Development Program of China（No.2017YFA0303703），Fundamental Research Funds for the Central Universities（Nos.021314380191，021314380105）

First author：LV Mingxin（1996—），male，master degree candidate，mainly focuses on solid-state laser. Email：mingxinlv@smail.nju.edu.cn

Received：Oct.10，2021；**Accepted**：Nov.24，2021

$$u(r,\varphi,z)=\sqrt{\frac{2p!}{\pi(|l|+p)!}}\frac{1}{w(z)}\left(\frac{\sqrt{2}\,r}{w(z)}\right)^{|l|}\exp\left(\frac{-r^2}{w^2(z)}\right)L_p^{|l|}\left(\frac{2r^2}{w^2(z)}\right)\times \exp\left(-\mathrm{i}k\frac{r^2}{2R(z)}\right)\exp(-\mathrm{i}l\varphi)\exp(-\mathrm{i}kz)\exp\left[\mathrm{i}\psi(z)\right] \tag{1}$$

where (r, φ, z) denotes the cylindrical coordinates and k is the wave vector. l (taking any integer value) is the azimuthal index of the LG beam and p (taking a zero or positive integer value) is the radial index. LG beam features a helical phase of exp ($\mathrm{i}l\varphi$) and a phase singularity at the center. Other types of vortex beam include high-order Bessel beams, hypergeometric Gaussian modes and helical-Ince-Gaussian modes[15-17]. In 2020, SHEN Y J et al proposed a new type of vectorial vortex beam, which is described as the superposition of SU (2) coherent states[18]. Such vectorially structured light features controllable degrees of freedoms in terms of coherent-state phase, OAM, polarization and trajectory shape, surpassing the limit of the traditional vortex beam (Fig.1).



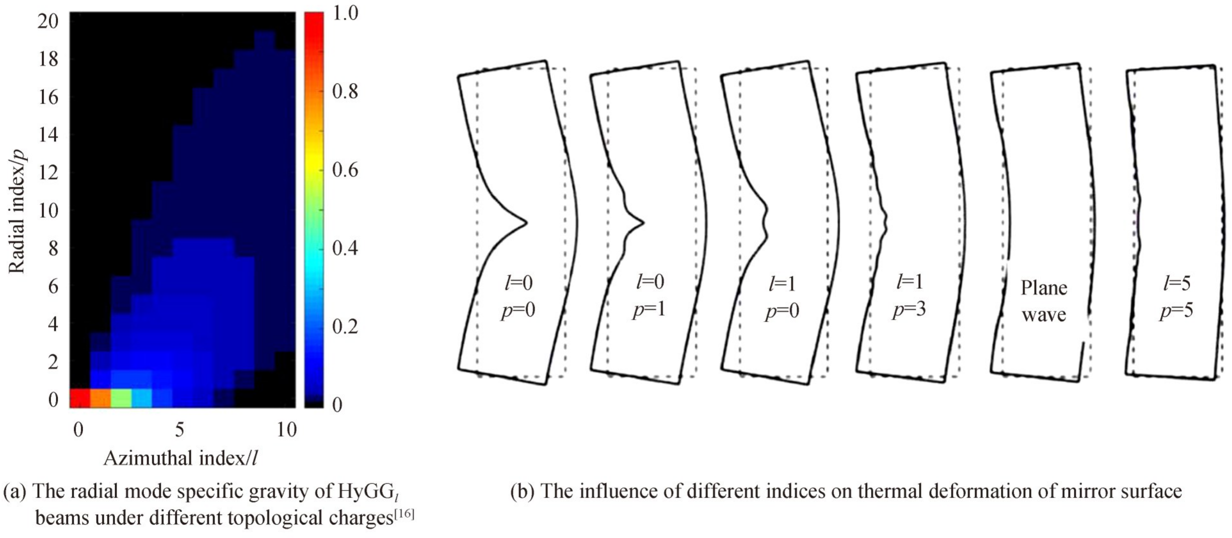
(a) Classical Poincaré sphere

(b) OAM Poincaré sphere

(c) Hermite-Laguerre-Gaussian (HLG) mode Poincaré sphere

Fig.1 Several generalized Poincaré sphere of SU(2) coherent state[18]

The methods of generating vortex beam can be divided into two categories, i. e., passive and active methods. The passive method generally loads the spiral phase into a Gaussian beam by using phase modulation elements such as forked gratings, Spiral Phase Plate (SPP), Vortex half-Wave Plate (VWP) and q-plate[19-24]. However, the vortex beam generated in these methods is generally a hypergeometric Gaussian(HyGG_l) mode, which is composed of multiple LG modes with the same l but various p, i.e., $u=\sum_{p=0}^{\infty}c_{lp}LG_{lp}$[16]. As shown in



(a) The radial mode specific gravity of HyGG_l beams under different topological charges[16]

(b) The influence of different indices on thermal deformation of mirror surface

Fig.2 The necessity of producing high purity vortex beam using active methods

Fig. 2(a), if we use a passive method to generate $l=1$ mode, only 78% of the energy is concentrated on $LG_{1,0}$ mode. The situation becomes worse when l increases. This will lead to severe problems when the applications require a high-purity LG mode[25-27]. For example, high-order LG beam can be used in Laser Interferometer Gravitational-wave Observatory (LIGO) system to detect gravitational wave[13]. As shown in Fig. 2(b), the thermal deformation of mirror surface can be significantly suppressed by using an LG mode with high l and p indices. In this case, high mode purity is the key to enhance the signal-to-noise ratio. Therefore, in order to improve the mode purity, it is necessary to filter out the unwanted modes, which generally leads to complex system and low conversion efficiency. Under such circumstances, the active method of vortex beam laser is viewed as a promising way to obtain a high-quality vortex beam. Next, we focus on the recent development of vortex beam lasers.

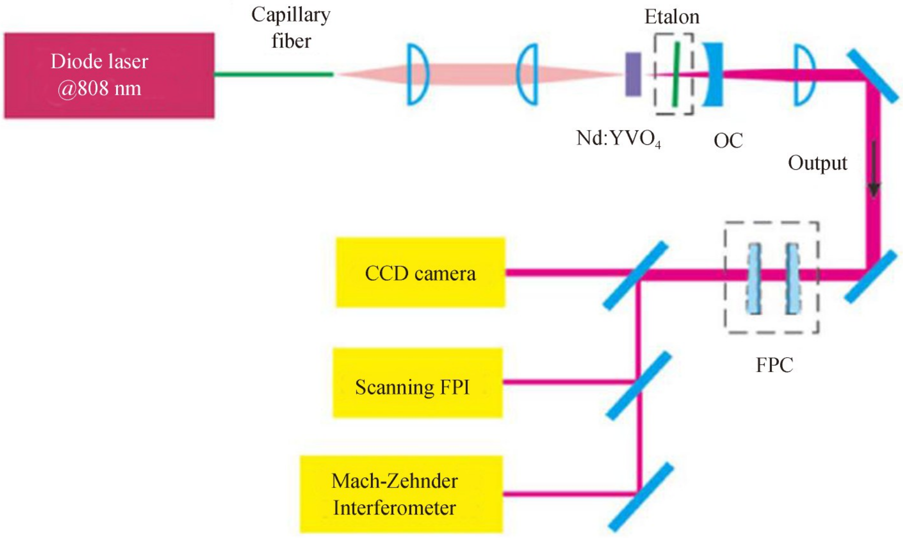
2 Laser output of a vortex beam

Unlike the passive generation of a vortex beam, the active way uses the properties of a laser resonant cavity to directly output a vortex beam. It is critical to carefully design the laser cavity, such as controlling the gain and loss of the cavity modes, matching the self-reproduction condition in cavity, and so on, to ensure the purity of the desired vortex beam mode. The following will be introduced in detail from the aspects of solid-state lasers, optical parametric oscillations, fiber lasers and integrated lasers.

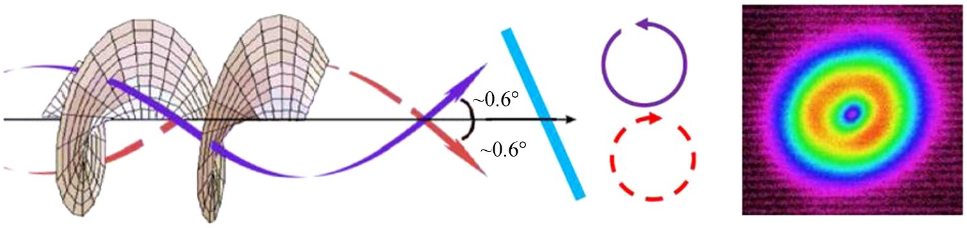
2.1 Solid-state vortex lasers

The solid-state vortex laser was first developed. In principle, one can obtain different laser output modes through proper design of the resonator. For a resonant cavity, it is also possible to output multiple different eigen modes at the same time. In general, one can effectively control one or more modes to output by manipulating the gain and loss of various modes in the cavity. As an example, when one need to output a Gaussian mode, it is effective to suppress other higher-order cavity modes. Similarly, if we need a vortex beam to output, other modes including the Gaussian mode have to be suppressed[28-31].

Pump shaping is an effective way to accomplish this task. When shaping the pump into a ring-shaped beam, the vortex beam mode is effectively amplified while the Gaussian mode is not. In 2005, BISSON J F et al realized a high-order vortex beam through hollow-shape pumping[29]. They input a pulsed laser beam having a wavelength $\lambda=0.532$ μm on a circular diaphragm to produce a hollow intensity distribution in the near field. Then, they used this beam to pump an Nd:YAG laser and obtained the laser output of LG modes, the order of which ranged from 1 to more than 200. In 2015, KIM D J et al obtained the output of two degenerated LG beams with opposite values of l using a ring-shaped pumping beam[30]. To obtain a pure LG beam, they used a tilted etalon inside the resonator, which broke the propagation symmetry of the Poynting vectors with opposite



(a) Experimental setup



(b) Schematic of two opposite LG modes and beam profile with an etalon

Fig.3 The experimental setup with a tilted etalon for laser output of an LG beam[30]

helicity (Fig.3).

A vortex laser can be achieved by introducing an additional loss of the Gaussian mode in a resonant cavity[32-35]. In 2010, ITO A et al generated both scalar and vector hollow beams using a side-pumped Nd:YAG laser cavity[32]. To suppress the oscillation of lower-order transverse modes, they used a mirror with a low-reflectivity central spot. In experiment, they generated a hollow scalar beam (LG beam) and vector beams (LG and Bessel-Gaussian beams). In 2011, NAIDOO D et al output a vortex beam by placing a stop in front of the output coupler in a cavity[33]. In this way, they generated a coherent superposition of two LG modes yielding "petal" modes in a standard Fabry - Pérot laser cavity. The azimuthal mode order was up to 8 by adjusting the stop. In 2010, THIRUGNANASAMBANDAM M P et al used a simple short-focus plano-convex glass lens with strong spherical aberration for Laguerre - Gaussian mode selection in a Continuous Wave (CW) laser-diode-end-pumped Yb: YAG ceramic laser[36]. They observed a sequence of LG modes with different combinations of radial and azimuthal indices (p=0～12, l=0～28). The output power was up to 30 mW at a wavelength of 1 030 nm.

One recently-developed method to generate a vortex beam is using spiral phase modulation elements in a cavity[36-42]. The advantage of this method mainly lies in high purity of the generated vortex beam. After the phase modulation element is added, the condition of the self-reproduction of the mode in the cavity must be properly satisfied to allow the vortex beam output. Here, we use VWP as an example to demonstrate the conversion process. VWP can be regarded as a half-wave plate whose direction of the fast axis changes with the azimuthal angle. Its Jones matrix can be expressed as

$$\boldsymbol{M}(\alpha)=\begin{pmatrix}\cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & -\cos 2\alpha\end{pmatrix} \tag{2}$$

where α is the orientation angle of the fast axis of the VWP. The relationship between α and the azimuthal angle θ is

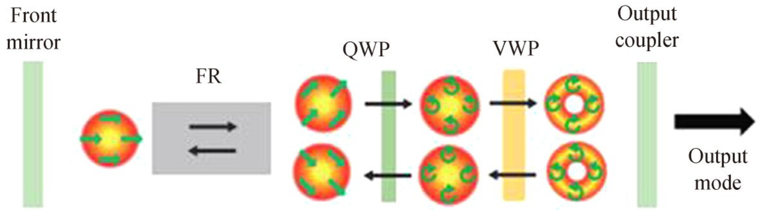
$$\alpha(\theta)=\frac{l}{2}\theta+\alpha_0 \tag{3}$$

which is dependent on the OAM order l and the initial azimuthal angle of the fast axis α_0. For a Left Circularly Polarized (LCP) incident light, the transmitted light is

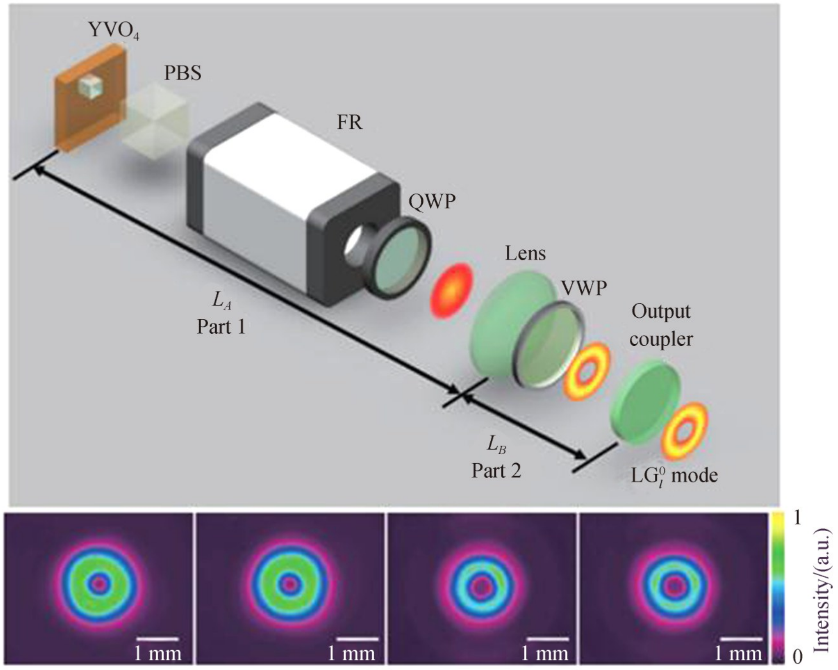
$$\boldsymbol{E}_1=\boldsymbol{M}(\alpha)\boldsymbol{E}_{\mathrm{LCP}}=\begin{pmatrix}\cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & -\cos 2\alpha\end{pmatrix}\cdot\frac{1}{\sqrt{2}}\begin{pmatrix}1 \\ -\mathrm{i}\end{pmatrix}=\mathrm{e}^{-\mathrm{i}l\theta}\mathrm{e}^{-\mathrm{i}2\alpha_0}\boldsymbol{E}_{\mathrm{RCP}} \tag{4}$$

where and are the Jones vectors of the LCP and Right Circularly Polarized (RCP) lights, respectively. Eq. (4) shows that the VWP can transform LCP light into RCP light carrying a spiral phase term of $\mathrm{e}^{-\mathrm{i}l\theta}$, and vice versa. A vortex beam can thus be obtained using circularly polarized light and a VWP. In 2016, NAIDOO D et al showed that any Higher-Order Poincaré (HOP) sphere beam can be directly generated by using intracavity phase modulation elements[41]. By controlling the relative angle between a quarter wave plate and a q-plate, they adjusted the geometric phase distribution in the output light to produce any arbitrary beam on the HOP sphere, including Cylindrical Vector (CV) vortex beams (such as azimuthally and radially polarized lights) and OAM modes. The mode purity was as high as >98%. In 2019, WEI D Z et al output the LG mode using reversible cavity mode conversion and appropriate cavity design[42]. By using a VWP, a Faraday Rotator (FR) and a Quarter-Wave Plate (QWP) in a Nd:$\mathrm{YVO_4}$ laser cavity, they realized the self-reproduction of the cavity mode and obtained low lasing thresholds (0.7 W for l=1 and 1.8 W for l=2), high slope efficiencies (11.06% for l=

1 and 5.11% for $l=2$）and high mode purities（97% for $l=1$ and 93% for $l=2$）of LG mode lasers（Fig.4）.



(a) The reversible condition for OAM mode generaton



(b) Experimental setup and the output intensity patterns

Fig.4　The experiment of LG beam laser with a VWP[42]

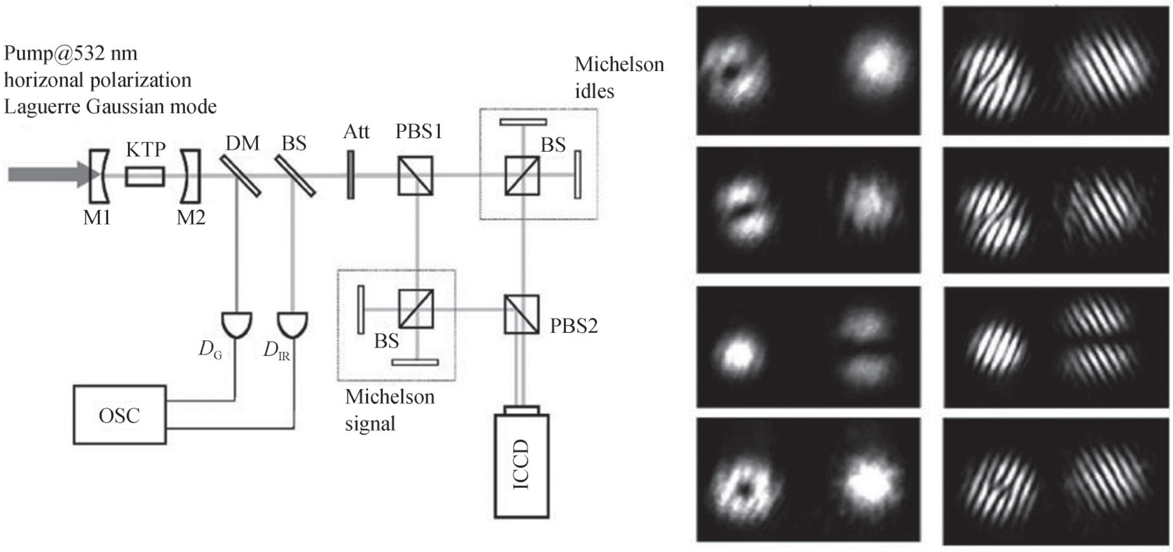
The use of SLM in a resonator makes it possible to produce different structured light fields through the loading of different holograms. In 2013，NGCOBO S et al used a phase-only reflective SLM to form a rewritable holographic mirror in place of the standard laser cavity mirror[40]. In principle，any light field can be output by loading the corresponding holograms on the SLM. In experiment，they generated HG modes，LG modes，and flat-top modes of different orders.

Recently，metasurface is utilized in a laser cavity for vortex beam generation. The unique advantage of this arrangement is that metasurface can be feasibly designed to realize specific phase modulations according to need. In 2020，SROOR H et al designed custom metasurfaces for arbitrary OAM coupling to linear polarization states，including one with an extreme helicity of up to $l=100$[43]. In this manner，they were also able to produce new chiral states of light from a laser，including simultaneous lasing across vastly differing and non-symmetric OAM values that are up to $\Delta l=90$ apart.

2.2　Vortex-beam optical parametric oscillator

Compared with solid-state lasers，the Optical Parametric Oscillator（OPO）produces different wavelengths of output light depending on the phase-matching conditions. By changing the temperature，cut angle，or the period of quasi-phase-matching crystal，OPO is able to generate a continuously-tunable wavelength range of the output light.

In 2004，MARTINELLI M et al investigated the transfer of OAM in an OPO system[44]. In experiment，they used a 10-mm-long KTP crystal，which was cut for noncritical phase matching at 1 064 nm. The OPO was pumped by an LG mode beam converted from HG mode beam using two cylindrical lenses. By controlling the depletion in cavity，they successfully achieved LG beam output in signal or idler mode（Fig.5）.



(a) Experimental setup

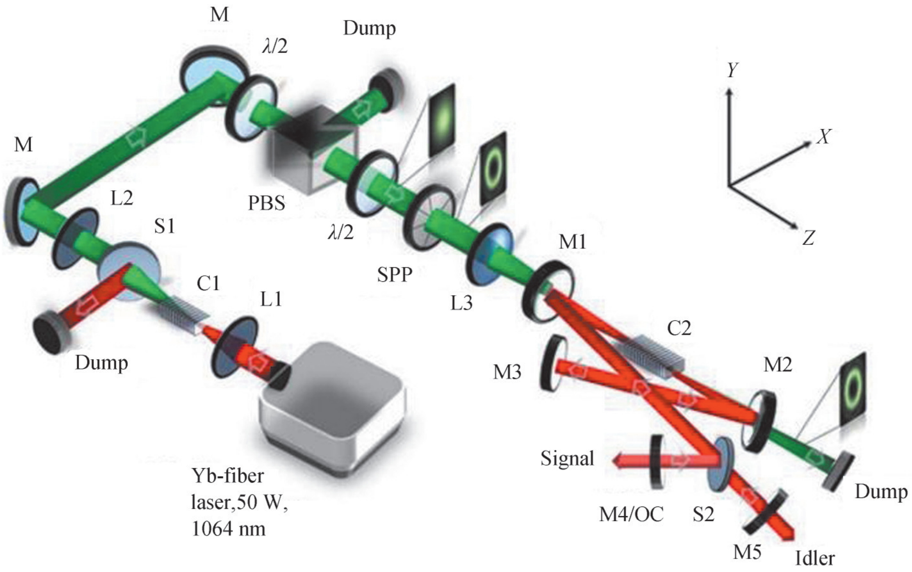
(b) Intensity patterns and self-interference patterns of output beam

Fig.5 The experiment of the vortex-beam OPO[44]

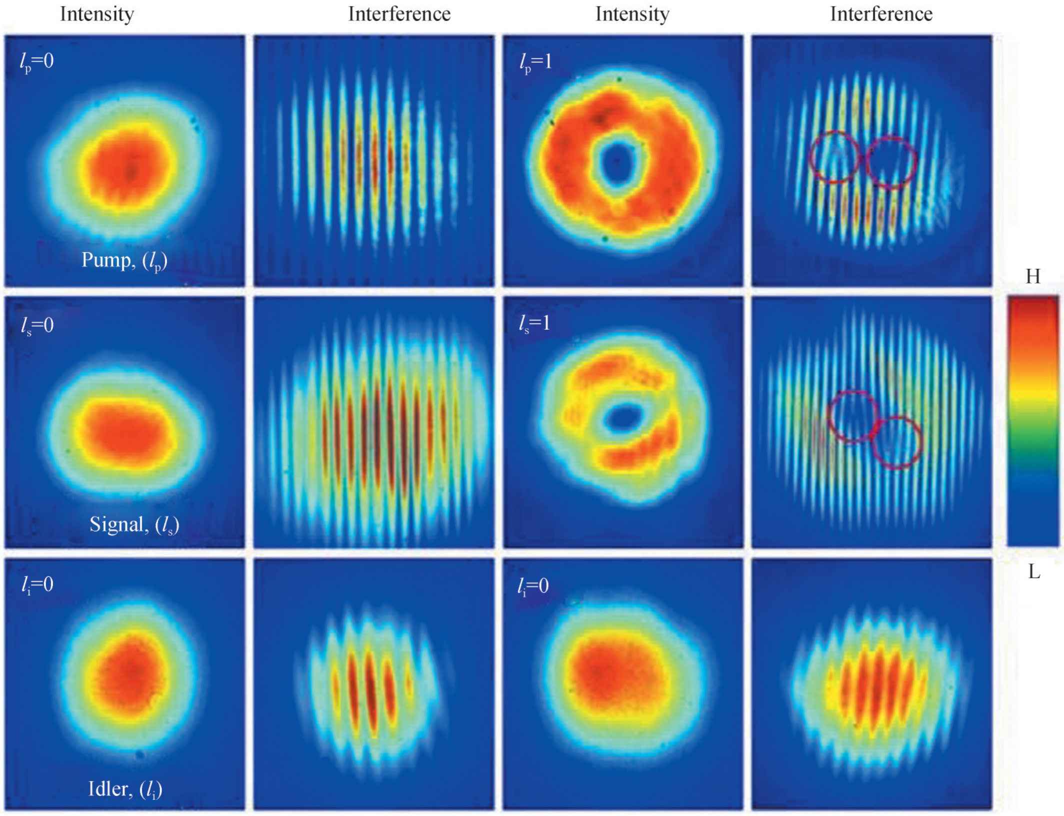
In 2011，MIYAMOTO K et al demonstrated a mid-infrared OPO pumped by a 1-μm optical vortex，and they created fractional vortex pulses having half-integer topological charge[45]. The fractional vortex pulse had an energy of 0.5 mJ and a width of 31 ns. The generation of 0.24-mJ mid-infrared vortices with a topological charge of 1 was also achieved. The tuning range covered the wavelengths from red to mid-infrared (735 nm～12.5 μm)[46-50].

In 2017，AADHI A et al realized a vortex-pumped continuous-wave OPO[51]. They used a doubly resonant oscillator and quasi-phase-matching nonlinear crystal to achieve a high gain and avoid anisotropy effects due to birefringence. They theoretically and experimentally verified that by controlling cavity losses，one can selectively transfer the OAM carried in the pump light to either the signal or idler light. The experimental setup and output beam patterns are shown in Fig.6. They showed that when pumping with the OAM states $|l_p|=1$ and $|l_p|=2$，the OPO has the two output states (|1，0> and |0，1>) and three output states (|2，0>，|1，1>，and |0，2>)，respectively.

Because of the low energy density of the vortex pumping light，the frequency conversion efficiencies in above OPO configurations are generally low. In 2020，WEI D Z et al proposed and experimentally realize highly-



(a) Experimental setup



(b) Intensity patterns and interference patterns of output beam

Fig.6 The experiment of OAM-mode-pumped doubly-resonant OPO[51]

demonstrated a Janus OPO system by introducing an intracavity mode conversion system, which is capable to efficient output of highly pure, broadly tunable and topological-charge-controllable LG modes[52]. A specially-designed imaging system was introduced into the cavity to guarantee the smooth conversion between the Gaussian mode and LG mode. The output LG mode had a tunable wavelength between 1.5 μm and 1.6 μm with a conversion efficiency above 15%, a topological charge switchable from −4 to 4, and a mode purity as high as 97%.

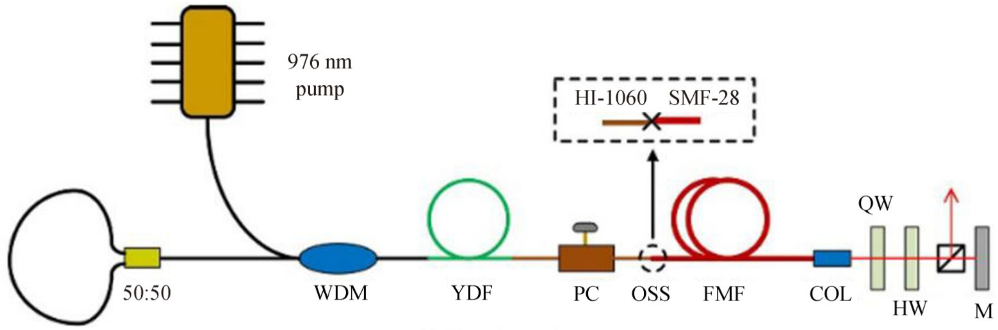
2.3 Fiber vortex lasers

A fiber laser typically uses glass fibers doped with rare earth elements as gain mediums. The fiber laser has good heat dissipation and excellent beam quality. Moreover, a fiber laser system is generally low-cost, which has undergone rapid development in recent years. The investigation of the fiber vortex beam laser has received increasing attentions for its application potentials in vortex-beam fiber optic communication[53-58].

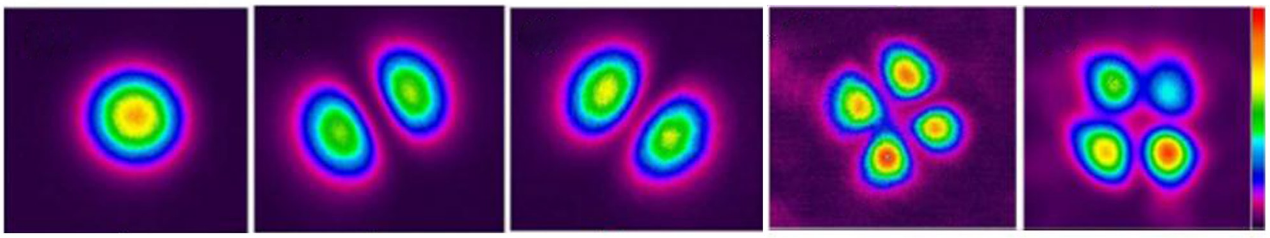
In 2016, ZHANG W D et al generated a vortex beam using an acoustically induced fiber grating driven by a radio frequency signal, which converted the left/right-handed circular-polarization fundamental mode to the +1/−1 order optical vortex in a two-mode fiber[55]. The mode conversion efficiency was kept at ~95% with a wavelength range of 1 540~1 560 nm by tuning the frequency of the radio frequency driving signal.

In 2017, WANG T et al generated high-order pulse vortex beams using a mode-locked fiber laser[56]. They fused a mode-selective coupler using a Single-Mode Fiber (SMF) and a Few-Mode Fiber (FMF) and converted the LP_{01} mode to a broadband LP_{11} (LP_{21}) mode. The measured durations of the vortex beam pulses were 273 fs and 140 fs for $OAM_{\pm1}$ and $OAM_{\pm2}$ modes, respectively. The maximal single-pulse energy was 0.36 nJ, which can be improved by increasing the pump power or reducing the loss of the SMF-FMF coupler.

In 2021, SHA W et al used a polarization rotation technique to select the fiber laser output mode[57]. By rotating waveplates inside the cavity, losses of different modes can be modulate. LP_{01} mode, LP_{11} mode, LP_{21} mode and vortex beams with topological charges of ±1 can be obtained from the fiber laser cavities(Fig.7).



(a) Experimental setup



(b) Output beam profile

Fig.7 The experiment of fiber vortex laser with polarization rotation technique[57]

2.4 On-chip integrated vortex lasers

Along with the rapid development of microfabrication techniques, the on-chip integrated vortex lasers has become a hot topic of research[59-65]. In 2001, CHEN Y F et al fabricated a double-end-pumped microchip laser to explore the output law of LG mode[59]. They found that two LG modes can be directly superposed without appreciable overlapping between their excited regions. In contrast, strong competition occurs when the inversion populations have considerable overlap. Later, they investigated the dynamics of transverse patterns in solid-state microchip lasers with a large Fresnel number. By controlling the transverse-mode spacing and the mode size, they generated a stable transverse pattern of optical vortex lattices.

In 2016, MIAO P et al realized the single-mode output of OAM microlaser[60]. They used a microring cavity supporting whispering gallery modes, which can output laser with a large OAM. In general, one needs to add a nonreciprocal isolator to break the reciprocity between the counter propagating waves in the microring cavity. By introducing complex-refractive-index modulations to form an exceptional point, the unidirectional propagation of waves was promoted. The topological charge and vector polarization states can be controlled by properly designing the resonator.

In 2019, ZHANG Z L et al directly generated a vortex beam from polarization mode selection in a dual-polarization microchip laser, which realized the simultaneous existence of TEM_{00} mode and LG mode with different frequencies and polarizations in the cavity[61]. Because of the frequency difference and spatial hole-burning effect, mode competition leaded to the generation of the x-polarized LG_{01} mode and y-polarized TEM_{00} mode, which can be easily separated with a polarizing beam splitter.

3 Conclusion

The vortex beam laser has experienced rapid development in recent years. Its applications have been extended from the traditional optical micromachining and optical manipulation to superresolution imaging, precision measurement, optical communications and optical information processing. These high-end applications significantly boost the requirements of high-quality vortex beam from various types of lasers. The development of high-performance vortex beam laser can also stimulate the research interests of fundamental physics involving the OAM of light, such as the manipulation of OAM in a nonlinear optical process, the OAM-enhanced capacity in quantum communications, and so on.

In future, there still remains many challenges for the vortex beam laser. As an example, it is critical to improve the output efficiency and power of the vortex beam laser. For certain extreme applications such as interferometric measurements in LIGO system, it requires high purity and high power output of high-order LG modes. In addition, the on-chip integrated vortex laser has attracted increasing research interests. It is exciting to anticipate a miniature laser device that output high-performance vortex beam.

References

[1] EINSTEIN A. On the quantum theory of radiation [J]. Physikalische Zeitschrift, 1917, 18: 121-128.

[2] ALLEN L, BEIJERSBERGEN M W, SPREEUW R J, et al. Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes [J]. Physical Review A, 1992, 45(11): 8185-8189.

[3] TOYODA K, MIYAMOTO K, AOKI N, et al. Using optical vortex to control the chirality of twisted metal nanostructures [J]. Nano Letters, 2012, 12(7): 3645-3649.

[4] AMBROSIO A, MARRUCCI L, BORBONE F, et al. Light-induced spiral mass transport in azo-polymer films under vortex-beam illumination [J]. Nature Communications, 2012, 3: 989.

[5] GIBSON G, COURTIAL J, PADGETT M, et al. Free-space information transfer using light beams carrying orbital angular momentum [J]. Optics Express, 2004, 12(22): 5448-5456.

[6] WILLNER A E, REN Y, XIE G, et al. Recent advances in high-capacity free-space optical and radio-frequency communications using orbital angular momentum multiplexing [J]. Philosophical Transactions of the Royal Society A-Mathematical, Physical and Engineering Sciences, 2017, 375(2087): 20150439.

[7] WEI D Z, ZHU Y Z, ZHONG W H, et al. Directly generating orbital angular momentum in second-harmonic waves with a spirally poled nonlinear photonic crystal [J]. Applied Physics Letters, 2017, 110(26): 261104.

[8] WANG A, ZHU L, CHEN S, et al. Characterization of LDPC-coded orbital angular momentum modes transmission and multiplexing over a 50-km fiber [J]. Optics Express, 2016, 24(11): 11716-11726.

[9] HAMAZAKI J, MORITA R, CHUJO K, et al. Optical-vortex laser ablation [J]. Optics Express, 2010, 18(3): 2144-2151.

[10] ASHKIN A, DZIEDZIC J M, BJORKHOLM J E, et al. Observation of a single-beam gradient force optical trap for dielectric particles [J]. Optics Letters, 1986, 11(5): 288-290.

[11] O'NEIL A T, MACVICAR I, ALLEN L, et al. Intrinsic and extrinsic nature of the orbital angular momentum of a light beam [J]. Physical Review Letters, 2002, 88(5): 053601.

[12] FANG X, YANG G, WEI D, et al. Coupled orbital angular momentum conversions in a quasi-periodically poled LiTaO (3) crystal [J]. Optics Letters, 2016, 41(6): 1169-1172.

[13] HONG T, MILLER J, YAMAMOTO H, et al. Effects of mirror aberrations on Laguerre-Gaussian beams in interferometric gravitational-wave detectors [J]. Physical Review D, 2011, 84(10): 102001.

[14] LIU Z X, LIU Y Y, KE Y G, et al. Geometric phase Doppler effect: when structured light meets rotating structured materials [J]. Optics Express, 2017, 25(10): 11564-11573.

[15] LITVIN I A, FORBES A. Bessel-Gauss resonator with internal amplitude filter [J]. Optics Communications, 2008, 281(9): 2385-2392.

[16] SEPHTON B, DUDLEY A, FORBES A. Revealing the radial modes in vortex beams [J]. Applied Optics, 2016, 55(28): 7830-7835.

[17] BENTLEY J B, DAVIS J A, BANDRES M A, et al. Generation of helical Ince-Gaussian beams with a liquid-crystal display [J]. Optics Letters, 2006, 31(5): 649-651.

[18] SHEN Y J, WANG Z Y, FU X, et al. SU(2) Poincare sphere: A generalized representation for multidimensional structured light [J]. Physical Review A, 2020, 102(3): 031501.

[19] BEIJERSBERGEN M W, COERWINKEL R P C, KRISTENSEN M, et al. Helical-wavefront laser beams produced with a spiral phaseplate [J]. Optics Communications, 1994, 112(5-6): 321-327.

[20] OEMRAWSINGH S S, HOUWELINGEN J AVAN, ELIEL E R, et al. Production and characterization of spiral phase plates for optical wavelengths [J]. Applied Optics, 2004, 43(3): 688-694.

[21] MARRUCCI L. The q-plate and its future [J]. Journal of Nanophotonics, 2013, 7(1): 078598.

[22] LIU Y, KE Y, ZHOU J, et al. Generation of perfect vortex and vector beams based on Pancharatnam-Berry phase elements [J]. Scientific Reports, 2017, 7(1): 44096.

[23] LIU Z, LIU Y, KE Y, et al. Generation of arbitrary vector vortex beams on hybrid-order Poincaré sphere [J]. Photonics Research, 2016, 5(1): 15-21.

[24] SHU W X, LING X H, FU X Q, et al. Polarization evolution of vector beams generated by q-plates [J]. Photonics Research, 2017, 5(2): 64-72.

[25] CHELKOWSKI S, HILD S, FREISE A. Prospects of higher-order Laguerre-Gauss modes in future gravitational wave detectors [J]. Physical Review D, 2009, 79(12): 122002.

[26] YU W T, JI Z H, DONG D S, et al. Super-resolution deep imaging with hollow Bessel beam STED microscopy [J].

Laser & Photonics Reviews, 2016, 10(1): 147-152.

[27] KRENN M, MALIK M, ERHARD M, et al. Orbital angular momentum of photons and the entanglement of Laguerre-Gaussian modes [J]. Philosophical Transactions of the Royal Society A-Mathematical, Physical and Engineering Sciences, 2017, 375(2087): 20150442.

[28] CHEN Y F, LAN Y P. Dynamics of the Laguerre Gaussian TEM0,l* mode in a solid-state laser [J]. Physical Review A, 2001, 63(6): 063807.

[29] BISSON J E, SENATSKY Y, UEDA K I. Generation of Laguerre-Gaussian modes in Nd : YAG laser using diffractive optical pumping [J]. Laser Physics Letters, 2005, 2(7): 327-333.

[30] KIM D J, KIM J W. Direct generation of an optical vortex beam in a single-frequency Nd: YVO4 laser [J]. Optics Letters, 2015, 40(3): 399-402.

[31] LIN D, DANIEL J M, CLARKSON W A. Controlling the handedness of directly excited Laguerre-Gaussian modes in a solid-state laser [J]. Optics Letters, 2014, 39(13): 3903-3906.

[32] ITO A, KOZAWA Y, SATO S. Generation of hollow scalar and vector beams using a spot-defect mirror [J]. Journal of the Optical Society of America A-Optics Image Science and Vision, 2010, 27(9): 2072-2077.

[33] NAIDOO D, AïT-AMEUR K, BRUNEL M, et al. Intra-cavity generation of superpositions of Laguerre - Gaussian beams [J]. Applied Physics B, 2011, 106(3): 683-690.

[34] KIM D J, KIM J W, CLARKSON W A. Q-switched Nd: YAG optical vortex lasers [J]. Optics Express, 2013, 21 (24): 29449-29454.

[35] NGCOBO S, AIT-AMEUR K, PASSILLY N, et al. Exciting higher-order radial Laguerre-Gaussian modes in a diode-pumped solid-state laser resonator [J]. Applied Optics, 2013, 52(10): 2093-2101.

[36] THIRUGNANASAMBANDAM M P, SENATSKY Y, UEDA K. Generation of very-high order Laguerre-Gaussian modes in Yb: YAG ceramic laser [J]. Laser Physics Letters, 2010, 7(9): 637-643.

[37] ABRAMOCHKIN E, LOSEVSKY N, VOLOSTNIKOV V. Generation of spiral-type laser beams [J]. Optics Communications, 1997, 141(1-2): 59-64.

[38] ORON R, DAVIDSON N, FRIESEM A A, et al. Efficient formation of pure helical laser beams [J]. Optics Communications, 2000, 182(1-3): 205-208.

[39] CALEY A J, THOMSON M J, LIU J S, et al. Diffractive optical elements for high gain lasers with arbitrary output beam profiles [J]. Optics Express, 2007, 15(17): 10699-10704.

[40] NGCOBO S, LITVIN I, BURGER L, et al. A digital laser for on-demand laser modes [J]. Nature Communications, 2013, 4: 2289.

[41] NAIDOO D, ROUX F S, DUDLEY A, et al. Controlled generation of higher-order Poincare sphere beams from a laser [J]. Nature Photonics, 2016, 10(5): 327-332.

[42] WEI D Z, CHENG Y, NI R, et al. Generating controllable Laguerre-Gaussian laser modes through intracavity spin-orbital angular momentum conversion of light [J]. Physical Review Applied, 2019, 11(1): 014038.

[43] SROOR H, HUANG Y W, SEPHTON B, et al. High-purity orbital angular momentum states from a visible metasurface laser [J]. Nature Photonics, 2020, 14(8): 498-503.

[44] MARTINELLI M, HUGUENIN J A O, NUSSENZVEIG P, et al. Orbital angular momentum exchange in an optical parametric oscillator [J]. Physical Review A, 2004, 70(1): 013812.

[45] MIYAMOTO K, MIYAGI S, YAMADA M, et al. Optical vortex pumped mid-infrared optical parametric oscillator [J]. Optics Express, 2011, 19(13): 12220-12226.

[46] YUSUFU T, TOKIZANE Y, YAMADA M, et al. Tunable 2-μm optical vortex parametric oscillator [J]. Optics Express, 2012, 20(21): 23666-23675.

[47] ABULIKEMU A, YUSUFU T, MAMUTI R, et al. Widely-tunable vortex output from a singly resonant optical parametric oscillator [J]. Optics Express, 2015, 23(14): 18338-18344.

[48] ARAKI S, SUZUKI K, NISHIDA S, et al. Ultra-broadband tunable (0.67-2.57 μm) optical vortex parametric oscillator [J]. Japanese Journal of Applied Physics, 2017, 56(10): 012701.

[49] YUSUFU T, NIU S, TUERSUN P, et al. Tunable 3 μm optical vortex parametric oscillator [J]. Japanese Journal of Applied Physics, 2018, 57(12): 122701.

[50] NIU S, WANG S, ABABAIKE M, et al. Tunable near- and mid-infrared (1.36 - 1.63 μm and 3.07 - 4.81 μm) optical vortex laser source [J]. Laser Physics Letters, 2020, 17(4): 045402.

[51] AADHI A, SAMANTA G K, KUMAR S C, et al. Controlled switching of orbital angular momentum in an optical parametric oscillator [J]. Optica, 2017, 4(3): 349-355.

[52] WEI D, CHEN P, HU X, et al. Generations of high efficiency, purityhigh, and broadband Laguerre-Gaussian modes from a Janus optical parametric oscillator [J/OL]. 2020, arXiv: 2004.12384 [https://ui. adsabs. harvard. edu/abs/2020arXiv200412384W.

[53] SUN B A, WANG A T, XU L X, et al. Low-threshold single-wavelength all-fiber laser generating cylindrical vector beams using a few-mode fiber Bragg grating [J]. Optics Letters, 2012, 37(4): 464-466.

[54] KOYAMA M, SHIMOMURA A, MIYAMOTO K, et al. Frequency-doubling of an optical vortex output from a stressed Yb-doped fiber amplifier [J]. Applied Physics B-Lasers and Optics, 2014, 116(2): 249-254.

[55] ZHANG W, WEI K, HUANG L, et al. Optical vortex generation with wavelength tunability based on an acoustically-induced fiber grating [J]. Optics Express, 2016, 24(17): 19278-19285.

[56] WANG T, WANG F, SHI F, et al. Generation of femtosecond optical vortex beams in all-fiber mode-locked fiber laser using mode selective coupler [J]. Journal of Lightwave Technology, 2017, 35(11): 2161-2166.

[57] WANG S, ZHANG Z C, WU Y J, et al. Vortex generation from a fiber laser by a polarization rotation technique [J]. Laser Physics Letters, 2021, 18(3): 035301.

[58] HUANG B, YANG L L, DU L, et al. Highly efficient vectorial fiber laser with switchable output [J]. IEEE Photonics Technology Letters, 2017, 29(21): 1852-1855.

[59] CHEN Y F, LAN Y P. Laguerre-Gaussian modes in a double-end-pumped microchip laser: superposition and competition [J]. Journal of Optics B-Quantum and Semiclassical Optics, 2001, 3(3): 146-151.

[60] MIAO P, ZHANG Z, SUN J, et al. Orbital angular momentum microlaser [J]. Science, 2016, 353(6298): 464-467.

[61] ZHANG Z L, GUI K, ZHAO C M, et al. Direct generation of vortex beam with a dual-polarization microchip laser [J]. IEEE Photonics Technology Letters, 2019, 31(15): 1221-1224.

[62] AHMED M A, VOSS A, VOGEL M M, et al. Multilayer polarizing grating mirror used for the generation of radial polarization in Yb : YAG thin-disk lasers [J]. Optics Letters, 2007, 32(22): 3272-3274.

[63] HAYENGA W E, PARTO M, REN J, et al. Direct generation of tunable orbital angular momentum beams in microring lasers with broadband exceptional points [J]. ACS Photonics, 2019, 6(8): 1895-1901.

[64] COGNéE K G, DOELEMAN H M, LALANNE P, et al. Generation of pure OAM beams with a single state of polarization by antenna-decorated microdisk resonators [J]. ACS Photonics, 2020, 7(11): 3049-3060.

[65] MA X, ZHENG S, LIU J, et al. Design of a single-mode directly modulated orbital angular momentum laser [J]. Chinese Optics Letters, 2021, 19(8): 081401.

Research Progress of Vortex Beam Laser (Invited)

LV Mingxin[1,2], ZHANG Yipeng[1,3], HE Jianlang[1,2], HU Xiaopeng[1,2], ZHANG Yong[1,2]
(1 *National Laboratory of Solid State Microstructures*, *Nanjing University*, *Nanjing* 210093, *China*)
(2 *College of Engineering and Applied Sciences*, *Nanjing University*, *Nanjing* 210093, *China*)
(3 *School of Physics*, *Nanjing University*, *Nanjing* 210093, *China*)

Abstract: The vortex beam laser outputs a high-energy and high-quality vortex beam, which is one typical structured light field. Vortex beam has potential applications in many important fields, such as optical communications, optical manipulation, precision measurement, quantum information, and superresolution imaging. Therefore, how to efficiently generate high quality vortex beam has attracted considerable interests of research in recent years. In this paper, we first briefly introduce the generation principle and main applications of the vortex beam. There are two main ways of generating vortex beams, i.e., active method and passive method. Compared with active method, passive method generally suffers from low conversion efficiency and poor beam quality (especially for high order vortex beams). When a high quality vortex beam is needed, active method is a better choice. The active method generates vortex beams under laser configuration. For example, the high purity vortex beam can be generated by using the mode selection of the laser cavity. At present, the research focus on vortex beam laser is to improve the laser performance and the mode purity of the output vortex beam. In addition, the integration of vortex beam laser, which facilitates various commercial applications, is also a hot topic. Then, we review the recent progress of vortex beam lasers, including solid-state vortex laser, vortex-beam optical parametric oscillator, fiber vortex laser and on-chip integrated vortex lasers. Solid-state vortex laser is one of the most common methods to generate a vortex beam. By properly designing various types of resonators, one can generate the desired laser vortex mode while suppressing the unwanted ones. Taking Laguerre - Gaussian beams as an example, one can use the pump shaping technique to transform the pump beam from a Gaussian beam to a ring shaped intensity profile, which can effectively enhance the gain of the matched Laguerre - Gaussian cavity mode and decrease the gain of other modes. In addition, a tilted etalon can also be used in the resonant cavity to precisely control the gain and loss of different cavity modes. A recent method is to add spatial phase modulation elements (such as spiral phase plate, vortex half-wave plate, and so on) into the cavity. By satisfying the polarization and spatial mode self-reproduction condition of the cavity mode, the output beam can carry a specific spiral phase, i. e., one can obtain a desired vortex laser beam. Interestingly, the use of spatial light modulators and metasurface greatly enriches the types of output spatial light beams. By loading different holograms on the spatial light modulators or properly designing the structures of the metasurfaces, one can get various types of vortex modes, including those with large l and p indices that are difficult to be produced in the previous methods. Along with the foundation of solid state vortex laser, other forms of vortex beam lasers have also been rapidly developed in recent years. Vortex beam parametric oscillator can achieve the output of vortex beam with a tunable wavelength by controlling the phase matching conditions. Compared with the solid state vortex laser, the output wavelength band of vortex beam is greatly expanded. The fiber vortex laser uses the fiber configuration to output vortex beam. The low cost and high stability of the fiber laser can be effectively combined with the vortex beam output for practical applications in high capacity information transmission. This unique characteristic makes fiber vortex laser particularly useful in the field of optical fiber communication. The development of micro/nano fabrication techniques make it possible to integrate vortex lasers on a chip. Finally, we present the prospects of the future development of the vortex beam laser. High conversion efficiency and high mode purity are two critical requirements for high end applications of vortex beam lasers.

Key words: Vortex beam; Orbital angular momentum; Laser; Optical parametric oscillator; Fiber laser
OCIS Codes: 140.3300; 140.3410; 140.3580; 140.3510; 130.3120